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Developments in Icing Test Techniques for Aerospace Applications in the RAE Pyestock Altitude Test Facility

by

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RAE, Farnborough, Hampshire

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SUMMARY

The altitude test facilities at RAE Pyestock are used in support of clearance of aero-engines, intakes and helicopter rotors to operate under severe icing conditions. An important aspect of the work is the simulation of the wet icing cloud in terms of water concentration, mean droplet size and spectrum. Water spray rakes or booms have been developed for this activity and individual nozzles calibrated in a purpose built wind tunnel using a laser particle sizer. Although this paper mainly deals with the development of cloud simulation, it also includes a short description of the facilities and the capability for monitoring ice formation and shedding.

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ABSTRACT

The altitude test facilities at RAE Pyestock are used in support of clearance of aero-engines, intakes and helicopter rotors to operate under severe icing conditions. An important aspect of the work is the simulation of the wet icing cloud in terms of water concentration, mean droplet size and spectrum. Water spray rakes or booms have been developed for this activity and individual nozzles calibrated in a purpose built wind tunnel using a laser particle sizer. Although this paper mainly deals with the development of cloud simulation, it also includes a short description of the facilities and the capability for monitoring ice formation and shedding.

1 INTRODUCTION

The safe operation of civil and military aircraft and helicopters operating in weather conditions which can cause ice build-up on engine intakes, engine fan, compressor and helicopter rotor blades is a prime concern of the air worthiness authorities. Regulations have therefore been introduced in Europe and the USA which identify the test conditions with which aerospace vehicles in ground-based facilities must comply before clearance to fly in icing conditions is given. Such facilities can generate specified, consistent and repeatable altitude test conditions irrespective of the prevailing weather and therefore contribute to a considerable reduction in test time and cost. Clearance for flight in ice-forming conditions can also be carried out on non-flightworthy but representative and generic test vehicles which can also contribute to savings.

The Royal Aerospace Establishment, England, has two altitude test cells at Pyestock which permit icing tests to be performed at controlled conditions. These were primarily intended for steady-state and transient performance evaluation of air breathing missile and aero engines, but a capability for icing tests was recognised and incorporated at the design stage. Although there has been long experience of icing tests extending over twenty years, development of test techniques and equipment is a continuing process and significant improvements have recently been introduced. These are centred on one of the most important elements of the whole process, the simulation of the defined cloud.

Some icing clouds consist of a mixture of supercooled water droplets and particles of dry ice and completely different techniques are used for producing these two components of the cloud.

Water droplets are usually produced in the icing tunnel using an array of spray nozzles placed in the cold inlet air stream upstream of the test vehicle.

Customers seldom specify a requirement for mixed conditions and the subject of ice particle production has therefore not attracted the same development effort as the production of water droplets. It is thus not given prominence in this paper.

Two significant problems exist in performing representative icing tests, the production of a uniform droplet distribution and the measurement of the droplet spectrum leading to the derivation of the volume median diameter (VMD).

This paper begins by briefly reviewing the icing certification regulations. The test facilities at Pyestock are then described together with a brief description of the capability for monitoring ice formation and shedding. Finally, the development of water spray rakes is discussed, with particular attention paid to those parameters and features which influence the spray quality. The use of the calibration facility in exploring these variables and the development of special measurement equipment for that purpose is fully described.

2 REVIEW OF ICING REGULATIONS

Icing tests at Pyestock form part of an overall icing certification programme agreed between the manufacturer and one or more of the three regulatory authorities empowered to grant the relevant operational clearance for aerospace vehicles manufactured and/or tested in the United Kingdom (UK). These authorities are:-

(a) The UK Ministry of Defence Procurement Executive (MOD(PE)) which deals with military equipment covered by the appropriate Defence Standard.

(b) The British Civil Aviation Authority (CAA) which administers the Joint (European) Aircraft Requirements (JAR) applicable to modern transport aircraft and propulsion systems and also the old British Civil Aircraft Requirements which still apply to types originally certified to these regulations.

(c) The Department of Transportation of the United States of America (USA) Federal Aviation Administration which issues Federal Aviation Regulations (FAR) and associated Advisory Circulars which are applicable to UK manufactured aerospace equipment,[4] which is required to operate in America.

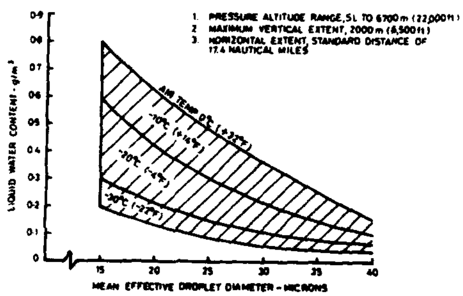
The Regulations, which apply to all authorities, demand that clearance to operate in icing conditions is dependant on a three-part assessment:

(a) An in-depth theoretical analysis of the susceptible icing areas on the flight vehicle at the most severe atmospheric conditions which may produce ice accretion and their affect on the vehicle as a whole.

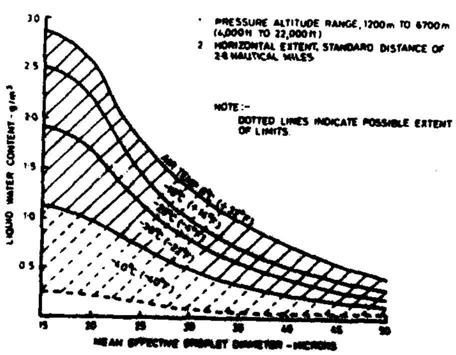
(b) Full-scale rig tests at these critical conditions.

(c) Flight tests performed in real icing environments.

All three regulatory authorities refer to the same two standard wet icing atmospheres detailed in Refs 5 to 8. These are the Maximum Continuous icing conditions relating to long tracts of stratiform cloud and the Maximum Intermittent icing typical of short span cumuliform cloud, illustrated in Fig 1.



STRATIFORM CLOUDS



CUMULIFORM CLOUDS

Fig. 1 Cloud characteristics

In general, the icing test requirements for the civil aircraft authorities quoted show, with some exceptions, very close agreement and it would appear that there is a gradual convergence towards a common policy covering all aspects of clearance to operate in natural icing conditions.

3 DESCRIPTION OF ICING FACILITIES

The altitude test facilities at Pyestock, pictured from overhead in Fig 2, consist of five test cells which are provided with air from a central compressor house. Exhauster-compressors in the building extract the exhaust gases and reduce the pressure in the test chamber to simulate the required altitude and also provide conditioned air at the cell inlet. The test article, be it aero engine or test rig, is mounted in the test cell and measurements of pressures, temperatures, fuel flow, thrust, etc are taken by a computer-controlled data-gathering and analysis system.

Two of the four active test cells, Cell 3 and Cell 3 West are able to cool their inlet air to the sub-zero temperatures required for icing. The former is used primarily for military engines and the latter for large civil fan engines. For normal icing tests a water spray rake is mounted in the inlet duct which injects a cloud of finely atomised water droplets into the air stream. An installation diagram of such an arrangement is shown in Fig 3. Both facilities have large test chambers; Cell 3 is 6m diameter and Cell 3 West, which has a diameter of 7.6m, is big enough to accommodate a helicopter fuselage (less rotors) as well as the latest civil fan engines. A majority of the aero engine testing is done in the connected mode, in which all of the inlet air is ducted into the front of the engine. Whenever plant capacity allows, however, it is preferred to test engines in conjunction with their intakes in the free jet mode, a method which is always applied to helicopter rigs. For this technique, air is discharged from a subsonic nozzle to envelope the test vehicle thus giving a better representation of the free-stream flow field.

There are significant differences between the two cells in the way the inlet air is conditioned, which affects the test envelopes and the relationship between the simulated and natural icing conditions. In Cell 3 West, air is induced from atmosphere through a 3-stage cross-flow heat exchanger connected to a refrigeration plant which can reduce the temperature to -37°C. In Cell 3, air is drawn from atmosphere and dried by passing through silica gel beds into the facility compressors, which then feed a proportion of the high pressure air after a further drying process into a cold air turbine (CAT) which reduces the temperature to a minimum value of -70°C. This cold air is then mixed with warm dry air in a chamber adjacent to the test cell to produce the required inlet air temperature. Thus, whereas the tests in

Fig. 2 Aerial view of test facility

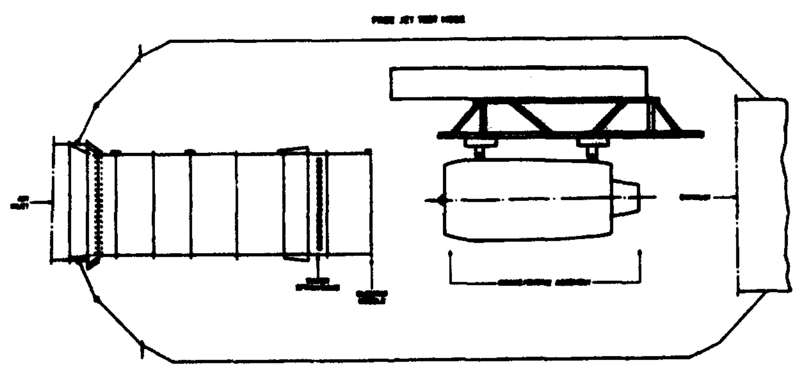


Fig. 3 Typical engine installation

Cell 3 West are limited by the rate of circulation of the coolant to between half an hour and three hours, Cell 3 can provide cold air continuously for periods of 3 to 4 hours, limited only by the air drying capacity.

A further difference between the two cells inlet conditioning systems is the effect on humidity. Ideally, the relative humidity of the air should be between 85 and 95% at the point where the droplets are injected so as to minimise the evaporation of droplets. Cell 3 has an advantage in this respect as the air is initially dried and brought up to the desired humidity using a steam injection system. Cell 3 West, on the other hand, has to accept whatever humidity levels occur following the partial freeze-drying of ambient air during its passage through the cooler. Experience shows, however, that this limitation can be accepted by avoiding icing tests in particularly humid or very dry conditions. Humidity is monitored using a Michell cooled mirror dew point probe placed in the low velocity air upstream of the spray rake which provides dew point temperatures from which the relative humidity at the water spray rake is then automatically calculated.

Fig 4 shows a typical installation of a spray rake. Four rake assemblies are available ranging from one with 37 nozzles for a 0.9 m dia duct to one with 310 nozzles for a 2.44 m dia duct. The water supply is demineralised and held in a tank at about 20°C and pressurised to 690 kPa (100 psia), flow being controlled by either multiple remotely-operated valves or variable speed pumps.

Fig. 4 Spray rake installation

The overall spray pattern of the various water injection rakes is checked in the test chamber. This is achieved by mounting a target grid of rods downstream of the spray rake and blowing air at a temperature no higher than -15°C with both high and low water flow rates. The low temperature ensures that all droplets impacting on the grid will freeze and the resulting ice accretion pattern when examined after 3 to 5 minutes of water injection gives an excellent indication of the uniformity of the spray.

Extensive facilities are available for viewing ice accretion and its subsequent shedding from the test vehicle. These include closed circuit TV, remotely operated high definition still cameras and high-speed ciné. For connected tests, camera viewing windows are mounted in the inlet duct. These are kept frost and mist free by electro-thermal heating. A typical still camera photograph of engine icing is shown in Fig 5.

Fig. 5 Ice accretion at engine inlet

4 PRODUCTION AND MEASUREMENT OF WATER DROPLETS

4.1 Spray nozzle

Airblast atomising nozzles are used to produce a cloud of water droplets, a typical nozzle being shown in Fig 6 comprising a central water nozzle surrounded by an annular air passage. Three different sizes of water nozzles are currently available depending on the liquid water content (LWC) range required. The high velocity of the atomising air relative to the water jet promotes the break-up of the water into fine droplets.

The whole Cell 3 West icing system was recently reviewed and in the light of many years experience of icing trials at Pyestock, various features were identified for improvement. Thence it was decided to manufacture three new sets of spray nozzles for the large spray rakes incorporating some of these improvements. Two of these sets were made with the same size water nozzles as the previous sets, ie 0.41 mm and 0.61 mm. The third set, at 0.76 mm, was larger than had been used before in anticipation of the higher water flows possibly required for future large turbofan engines.

The improvements incorporated were as follows:

(a) The nozzles were made in three parts rather than two (Fig 6) allowing positive central location of the air cap with respect to the water nozzle, independent of the concentricity of the locking nut.

(b) The water nozzle was made of stainless steel instead of brass making the protruding nozzle less vulnerable to mechanical damage and chemical attack from the de-mineralised water.

(c) The locking nut was changed from a round knurled cylinder to a heptagonal nut allowing easier and more positive tightening of the nuts.

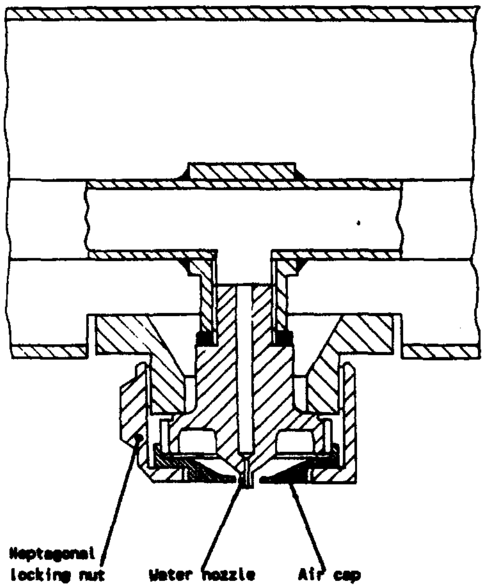


Fig. 6 New three-part spray nozzle

Because of these geometric changes it was necessary to confirm that the basic spray nozzle droplet size characteristics had not been affected and a cross calibration test programme was therefore undertaken. These tests brought to light some unexpected differences between the old and new nozzles.

For example, it was found that a higher water pressure was needed on the new nozzles to get the same water flow rate, and the minimum flow rate was reduced, even though the actual water nozzle internal diameter was nominally the same. This was attributed mainly to tighter tolerancing on the new nozzle dimensions leading to the water passage being slightly smaller and was most noticeable on the smallest, 0.41 mm, nozzles. Although the basic characteristics remained unchanged, this reduction in water flow could affect the selection of the nozzle sizes to provide the required LWC. Another problem which became evident during the testing of the new nozzles in the Spray Calibration Facility (SCF) was a decrease in the atomising efficiency. That is, with a given atomising air pressure at a given water flow, the VMD was greater with the new nozzles. Examination of old and new nozzles showed that there were probably two factors contributing to this. Firstly, the design of the new air cap channeled the air more than before, and secondly, the machining process on the six blind holes had thrown up small ridges of metal (burrs) at the top of the holes. The combination of these, a channel and a restriction, meant that for the same driving air pressure less air was emerging from the central annulus to atomise the water jet. Comparative air flow measurement on the same nozzle before and after 'de-burring' confirmed this. Similarly spray measurements showed that 'de-burring' restored the atomising performance of the nozzles.

There was concern that the change to the heptagonal locking nut, which was slightly more intrusive in the tunnel air stream than the round locking nut/air cap, might affect the spray characteristics. However, direct comparison made by testing the same nozzle fitted alternately with a single piece round and single piece heptagonal air cap showed little difference over a range of water flows apart from a tendency for the heptagonal cap to give VMDs about two microns lower. However, later investigations revealed that the heptagonal cap also had a lower pressure drop, resulting in a greater atomising air flow. This could well have contributed to the VMD reduction.

4.2 Water flow control

The control and accurate measurement of the water flow through the spray rake is important both for the realisation of the specified LWC and the production of correct droplet VMD. The water flowmeters used for this purpose are either of the Pelton wheel or turbine type and are calibrated before each icing installation using a dedicated traceable gravimetric calibration system.

On the 242 nozzle spray rake there is a fundamental problem in that a pressure head difference of up to 2.4 m between the top and bottom spray arms causes unequal water flows if not corrected. The current method of solution uses a water pressure control chamber of approximately 0.8 litre volume positioned on each spray arm. The chamber water level is maintained at a constant level by an optical sensor controlling a solenoid valve in the water inlet line to each chamber. This arrangement is shown in Fig 7. Each chamber is positioned so that the water level remains constant at 50 mm below the spray arm it is supplying. The flow of water through each spray arm is effected by displacing the water from the chambers by supplying nitrogen gas into the top of the chambers, the rate of water flow through the spray arms being controlled by the pressure of the applied nitrogen gas. A system of current to pressure converters and pneumatic multipliers enables the nitrogen pressure to the water chambers to be controlled remotely from the Engine Test Control Room. Whilst very successful in producing equal flows to the spray nozzles, this system is subject to pulsations in the water supply to the chambers caused by the continual opening and closing of the valves in the feed lines. This has made the instantaneous on-line measurement of total water flow difficult resulting in average values of water flow being used.

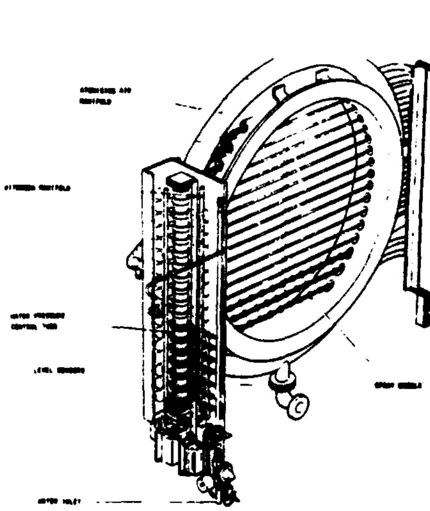


Fig. 7 Spray rake and control system

A new improved method of water flow control that provides controlled continuous flow is currently under development. This system will supply water to each spray arm by an electrically driven positive displacement pump regulated by a closed loop feedback circuit. The speed of each pump is controlled by the output of a differential pressure transducer measuring the spray rake arm water pressure referenced to the static duct pressure within the test cell. By controlling the pressure at each rake arm, constant spray rates will be achieved for spray rakes with different numbers of spray nozzles and varying test cell conditions. To provide the correct inlet pressure conditions at the inlet manifold to the spray rake pumps a separate priming pump and pressure feedback circuit, referenced to static duct pressure within the test cell, is incorporated in the design. Advantages of this new system will be the elimination of water flow pulsations; controlled water flow to each spray arm to cover the range of conditions specified in the icing certification regulations and a reduction in the time required to change spray rates in cyclic icing certification tests. The method of control will be much simpler compared with the earlier design with control parameters preset via a computer. The non-pulsating water spray rates during icing tests will greatly simplify the analysis of time variant water spray rates. The performance of each pump will be monitored on a digital read-out and a bar-type display.

4.3 Spray calibration facility

Ideally, the water droplet diameters should be measured in the test cell close to the test body. In practice this proves to be extremely difficult as both the scale of the testing and the semi-industrial conditions are not compatible with the sophisticated type of instrument required. This instrument has to be capable of measuring millions of droplets per second, ranging in size from a few to hundreds of microns. At Pyestock the alternative method of calibrating the nozzles in a separate Spray Calibration Facility (SCF) has been adopted.

The SCF (Fig 8), recently enhanced, comprises an open circuit wind tunnel with a 0.4 m diameter working section connected to exhausting machinery capable of generating air speeds up to 152 m/s (500 ft/s). Prior to the enhancement the twin nozzle spray mast had been inserted into the working section from the side which meant that the distance from the nozzle to the laser beam was fixed. In the test cell, depending on the test configuration, the engine inlet is between 1.5 and 4.9 m from the icing rake. In order to allow an equivalent variation the enhanced SCF has a steel tube mounted along its axis which serves both to support the nozzle arrays and contain the services. Two representative arrays can be mounted on the end of this long 'sting' incorporating four and seven nozzles respectively. This sting and nozzle(s) combination is then inserted at the mouth of the tunnel (Fig 9) allowing the sampling distance to be varied continuously. The water supplies are fed to each arm of the array individually through the sting. Selection of the number of arms/nozzles actually spraying can be made both by the control of the water to each arm and by blanking off nozzles.

Fig. 8 Enhanced Spray Calibration Facility

Fig. 9 Nozzle arrays and sting

A laser particle-sizer produced by Malvern Instruments straddles the working section with its beam directed through the droplet cloud. This instrument's principle of operation is as follows. The diffracted laser light pattern formed by the droplet cloud is detected by a photo-diode array. This generated signal is then converted into a droplet volume spectrum by proprietary software using a personal computer. A typical computer output showing a droplet distribution is shown in Fig 10. As can be appreciated, this widely accepted instrument is a major advance on earlier techniques based on the use of oiled or coated glass slides on which droplets were captured and photographed for later analysis.[10,11] The laser measuring system is non-intrusive, scans many thousands of droplets in a few seconds, produces on-line data and can be operated remotely.

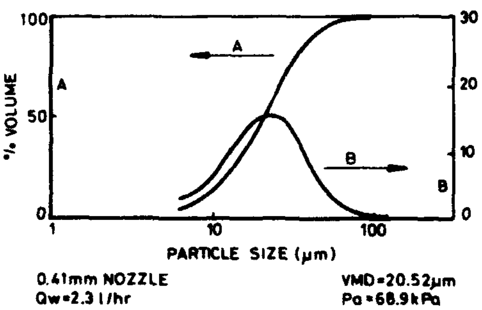


Fig. 10 Typical particle sizer display

To enable the measurement of a representative sample a certain proportion of the main laser beam must be scattered on to the diode detector; this condition has been satisfied in the past by using one nozzle with a tunnel air velocity of some 46 m/s. This beam obscuration decreases with tunnel air speed but more nozzles may now be selected if necessary to compensate for this. There is also the possibility that the additional spray may contaminate the lenses more rapidly leading to slower data-gathering because of more frequent to lens cleaning operations.

Various lenses can be used with the instrument to cover different particle size ranges and working distances. The latter is defined as that distance from the lens within which droplets can be measured accurately. Experience has shown that the best working arrangement is a 300mm lens which has a working distance of 400mm and a particle (droplet) size range of 5.8 to 564 microns. This working distance accords well with the 0.4 m tunnel width. The lower droplet size limit of 5.8 microns is not a disadvantage in practice as the aggregate volume of any droplets below this size will generally be a very small proportion of the total volume for the distributions typically produced by these nozzles. Additionally, the Malvern software makes some extrapolation for the undersize droplets.

Functional checks are made using a Verification Reticle. This consists of an optical glass flat, which can be attached to the receiving lens of the particle sizer, on which about 10000 chrome dots of known sizes are deposited randomly within an 8mm diameter circular area. The effective VMD of this array is initially determined by the manufacturers within a specified tolerance of ±2 microns. If the particle sizer repeats this measurement within the above tolerance then it is concluded that the system is functioning correctly. With such a complex opto-electronic system this simple technique is a very worthwhile performance monitor.

5 TYPICAL SPRAY NOZZLE CALIBRATIONS

5.1 Presentation of data

The direct plotting of the SCF droplet size data in terms of VMD versus atomising air pressure for a given water flow yields a repeatable well-defined smooth curve, known at Pyestock as a nozzle characteristic (Fig 11). This curve is asymptotic to both axes showing the practical limits of operation at any water flow. At one extremity it shows that further increases in atomising air pressure do not reduce the VMD significantly, giving the lower limit at that water flow. On the VMD axis it shows that at low atomising air pressures only small reductions in this quantity produces large increases in VMD making it impractical to work in this region. This occurs usually towards the higher VMD values, depending on the water flow rates, and outside the normal working range of the nozzles. It is also perhaps worthwhile pointing out that on this figure the data from four 0.76 mm nozzles have been plotted. There is little nozzle to nozzle variation giving some confidence in the uniformity of the generated cloud.

While these curves are extremely useful in checking the consistency of the SCF data they are not convenient for use in the altitude icing test facilities. In order to achieve the correct icing

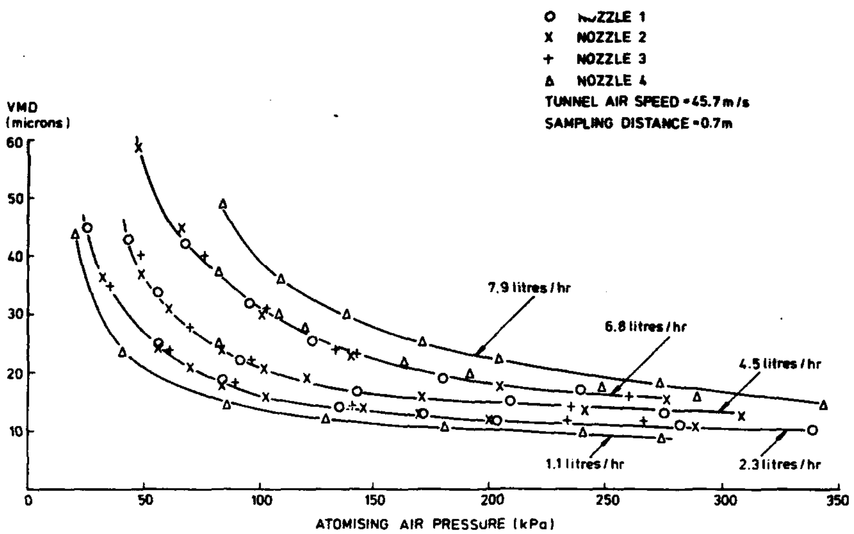


Fig. 11 Atomising characteristics of four 0.41 mm spray nozzles

conditions in the test cell the operator needs to know the atomising air pressure which has to be set to give the required VMD at the water flow, chosen to correspond to the required LWC. Curves showing this relationship can be derived by cross-plotting from the 'nozzle characteristics' using axes of water flow and atomising air pressure to produce 'working curves' as shown in Fig 12.

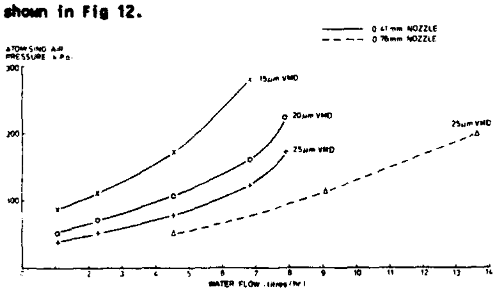


Fig. 12 Spray nozzle working curves

5.2 Effect of duct air speed

Previous work on the SCF with a larger working section showed a marked dependence of VMD on tunnel air speed up to the limit of 76 m/s. This dependence was one of the reasons for modifying the tunnel so that it could be investigated at the higher air speeds which could be encountered in actual icing tests. To date only preliminary investigations have been carried out using the central nozzle of the seven nozzle array in the enhanced facility at the same standard distance. Increasing air speeds up to 122 m/s at one water flow on a 0.76 mm nozzle has, however, not caused any significant change in the VMD, as shown in Fig 13. The reason for this discrepancy is unknown and clearly will be the subject of further work. One possible explanation being considered is that as the original SCF did not have an ideal intake flare the resulting turbulence may have distorted the spray plume, especially at high tunnel air speeds. This would cause the laser beam to sample different parts of the plume, resulting in VMD changes. The improved intake of the enhanced SCF would, of course, remove this effect.

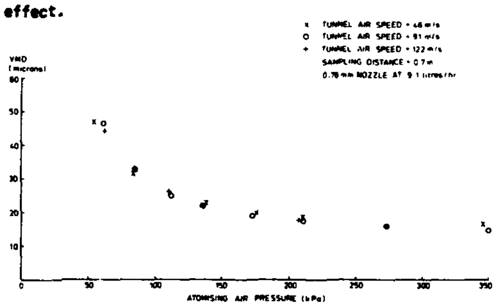


Fig. 13 Effect of tunnel air speed on VMD

5.3 Effect of main stream air temperature

As the demineralised water supply fed to the spray rake in the test cell is maintained at 20°C to prevent it freezing before or on reaching the nozzle, it may be questioned if the droplets have become supercooled and/or reached air stream temperature by the time they arrive at the target, as they would in a natural cloud. This is important because Merck & Bartlett and others have shown that ice accretion takes different forms depending on the state of the droplets at impact.[12] Theoretical studies at Pyestock suggest that while a 10 micron droplet comes to thermal equilibrium in a -5°C air stream in under a metre or so, a 30 micron droplet with 27 times more mass, might require 5 metres, although it would still be supercooled within about a metre.

Ideally, from this point of view, the separation between the spray rake and the target needs to be greater than 5 m to ensure fully representative ice accretion, although distances down to 3 m are probably acceptable.

6 CONCLUDING REMARKS

Although a solid data base on the Pyestock spray nozzles has been achieved there is considerable scope for further work mainly through extending the capability of the spray calibration facility and investigating different spray nozzle designs.

The former SCF maximum air velocity limit of 76 m/s was not fully representative of the velocities used in the actual icing tests and, as previously mentioned, this parameter may affect the droplet VMD. In the enhanced SCF the maximum velocity has been increased to 150 m/s enabling more representative calibration conditions to be generated.

All the measurements reported here have been made with the spray bar 0.7 m from the laser beam. This distance is often exceeded in icing tests and the effect of this is not known and needs to be investigated using the sting mounted nozzles. Increased evaporation or coalescence may occur, changing the VMD.

To date overall the SCF data gives reasonable confidence in the quality of the simulated cloud in the altitude test facility. In the range 15 to 40 microns the specified VMD can be produced at the required LWC on the basis of consistent and repeatable calibration data. The nozzle-to-nozzle variation has been established as being small, although confirmatory tests are needed, and the droplet size distribution is generally of a good form over a wide range of water flows. It can therefore be said that the icing conditions in the Pyestock altitude test facility meet the current certification regulations. Moreover, there is scope to cover any probable developments in these regulations.

Future work at RAE will thus continue to be aimed at meeting customer requirements and satisfying the evolving demands of the international regulatory authorities. In this respect, a document about to be published by the FAA entitled "The Aircraft Icing Technology Handbook" should stimulate international efforts towards producing a single comprehensive set of icing requirements aimed at worldwide application. International effort might also be appropriate to update the existing icing cloud characteristics bearing in mind that these are based on data gathered nearly forty years ago using flight instrumentation far less precise than modern equipment. Perhaps this should be extended to other parts of the globe not previously surveyed.' The test facilities at Pyestock could play a role in this work by evaluating the latest flight-standard instruments.

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17. Abstract

The altitude test facilities at RAE Pyestock are used in support of clearance of aero-engines, intakes and helicopter rotors to operate under severe icing conditions. An important aspect of the work is the simulation of the wet icing cloud in terms of water concentration, mean droplet size and spectrum. Water spray rakes or booms have been developed for this activity and individual nozzles calibrated in a purpose built wind tunnel using a laser particle sizer. Although this paper mainly deals with the development of cloud simulation, it also includes a short description of the facilities and the capability for monitoring ice formation and shedding.